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Effect of operating and surrounding conditions on cooling load of air conditioned cars#

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ABSTRACT

The demand for air conditioned cars has been increasing at a rapid rate due to increasing standard of living and adverse climatic conditions. The heating, ventilation and air conditioning system can reduce the fuel economy of a mid-size conventional vehicle by as much as 20%. Depending on the capacity of the air conditioning system and drive cycle, the range of Electric Vehicle (EV) and fuel economy of Hybrid Electric Vehicle (HEV) can reduce by approximately 40% under normal air conditioning loads. Thus, it is a challenge to maintain thermal comfort of the passengers and driver with minimum energy consumption. Hence proper indoor environment management of the passenger vehicle is of high priority. Thus, proper design, selection and operation of the car air conditioning system play an important role. The first step in this direction is proper estimation of cooling load on the car under various operating and environmental conditions. The aim of the present study is to develop a simple cooling load calculation model suitable for stationary and running conditions of a passenger car and study the effect of parking and operating conditions on the cooling load. The variation of cooling load of the running car is analysed by varying car speed, time of the day etc. Similarly, for the parked car the parametric analysis is done with respect to orientation of the car, exterior colour of car, ground reflectivity of parking zone base materials etc. Results show that there is 10% reduction in sensible cooling load as the car speed varies from 20 to 75 kilometers per hour. Choice of insulation material of car can affect the cooling load by about 3 %. The external colour and parking place ground reflectance can affect the heat transferred by about 14%. The heat transfer rate on the car reduced by 22.5 % when a white car with tinted glass at side windows and rear windshield, is parked on grass base, compared to a black car with normal glass parked on concrete base. It is expected that this study is useful in design of the energy efficient cars through suitable design and operating interventions.

Keywords: Air-conditioned cars, Cooling load, Ground reflectance, Car speed, Solar radiation

NONMENCLATURE

Abbreviations	
AC	Air Conditioning
DTM	Deep Thermal Mass
LST	Local Solar Time
WG	Window Glass
WS	Windshield
Symbols	
Β	Altitude angle (°)
б	Inclination angle (°)
ϴ	Angle of Incidence (°)
ω	Hour angle (°)
υ	Surface azimuth angle (°)
$\sum$	Tilt angle (°)
V	Velocity of air (m/s)
h	Heat transfer coefficient (W/m^2-K)
$T_{Surface}$	Surface temperature of car wall, glass, and roof (°C)
T_i	Cabin temperature (°C)
T_{infin}	Outside air temperature (°C)
α	Absorptivity
τ	Transmittivity
N	Fraction of absorbed radiation transfer to car cabin

1. INTRODUCTION

Air conditioning is widely applied in passenger transport sector for providing thermal comfort to the drivers and the passengers. Currently almost all the

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passenger cars are provided with air conditioning. People park the car under the sun because of lack of sufficient quantity of shaded parking [1]. As cars are made of metallic sheets, with insulation and large area of transparent glasses, solar radiation and heat from other external sources is easily transmitted into the cabin during summer. This creates a hot environment inside the car, and temperature may reach up to 80 ^{o}C and 50 ^{o}C on normal sunny and partially cloudy days, respectively [2-5]. This high temperature is intolerable without air conditioning system. The seat materials and other accessories store heat which delays temperature rise but retain heat for long time. This high temperature is life threatening for mistakenly locked kids and pets in the cars. These cases are found in many countries and is also applicable for Indian climate. If the temperature and air distribution inside the passenger compartment is not proper, the passengers and driver feel uncomfortable, and the driver may lose cognizance while driving [6]. On the other hand, air conditioning system reduces the fuel economy by around 20% for a mid-size passenger fuel operated vehicle and 40% of an HEV under normal air conditioning loads [7]. So, it is a big concurrent challenge to maintain thermal comfort along with fuel economy or mentioned range by the manufacturer of an EV. Due to heavy emissions from the vehicles, auto industry needs to reduce fuel consumption and tail pipe emissions. Studies show that NOx can increase by 15 to 100 % due to car air conditioning (AC), which uses as much as 12% of the total vehicle power for a mid-size car. Air

Fig.1 Photograph of Tata Tigor Car

conditioning is the second highest power consumer after electric motor in EV and HEVs. For design of efficient AC, a proper understanding of the heating and cooling loads is very important. To maintain thermal comfort within the cabin the air conditioning system needs to function as per the variation of cooling and heating load [8]. The hot soak study of the passenger car done by Waleed et al., found that the front and dashboard and back side board temperature is higher than other surfaces irrespective of direction [9]. In their investigation into the effects of varying solar radiation angles on passengers' thermal comfort, Tao et al. [10] found that while radiation at a solar altitude angle of 63.51^{o} was less than that at 90°, the human body's temperature exceeded the comfort range because of direct radiation on the body.

The literature available on hot soaking of a car mainly focused on experimental and simulation study. But detailed mathematical analysis of effect of operating and surrounding conditions on cooling load of air conditioned cars is very limited in literature. The study on variation of car's cooling load in tropical climate is not available. Thus, the aim of this study is:

I. Development of a mathematical model for estimation of heat gain of a stationary car and cooling load of a running car exposed to solar radiation.
II. To find the effect of environmental conditions, and materials on the heat transfer rate of car under parked and running conditions for the Indian tropical climate.

2. MODEL DEVELOPMENT

For the estimation of the heat transfer rate to the car, the vehicle interior is considered as lumped body. For cooling load calculation, the interiors are assumed to be at uniform and steady temperature, maintained by the air conditioning system of the car.

2.1 Material and methods

For the analysis, two different models are prepared

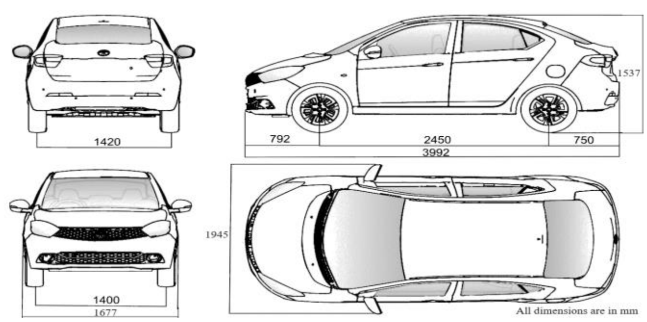

Fig. 2 Blue print of Tata Tigor [12]

and associated suitable conditions are considered with simplified assumptions. The analysis is done for Kharagpur location (22.35^{o}N, 87.23^{o}E) and June 21st. The first model is for parked car and second one is for running car. For both cases Tata Tigor (shown in Fig. 1) is taken as a base model. The associated outside dimensions of the car mentioned in the blue print of the car are shown in Fig. 2. The total outside surface area for heat transfer is approximately 11.5 m^{2}. The various thermal loads of the vehicle cabin are shown in Fig. 3. For the parking condition, the car is assumed to be parked facing east, west, south, and north from 7 am to 4 pm under the sun. For observing the effect of environmental parameters and body materials of car on heat gain of the car, different colours of car, parking zone materials and different type of window glasses are taken as variable parameters. The hourly solar radiation parameters and environmental temperatures are taken from ASHRAE [11] for calculating incident angle, declination angle, azimuthal angle and the heat gain on an hourly basis for each direction the car is facing.

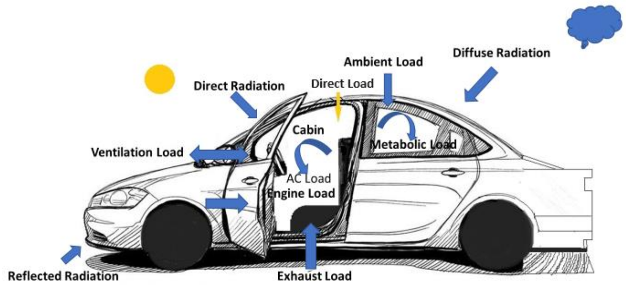

Fig. 3: A typical vehicle cabin thermal load

For the analysis of variation of cooling load at running condition, car speed, solar incidence angle, direct radiation through windshield, hourly temperatures, and number of occupants are taken as varying parameters. In this case only the solar angle is varied and car body materials are not taken as varying parameters for sake of brevity.

2.2 Mathematical formulation of the model

For the mathematical formulation of model at static and dynamic conditions of car, some simplified assumptions are made:

I. The doors and windows of the car are perfectly closed with no air leakages.
II. There is no curtain on the windows and rear windshield.
III. During running condition with the car, the sun is assumed at overhead position.
IV. Air conditioning system and fan are off during parking (hot soaking).
V. Heat capacity of the car walls is neglected.

Initially the white colour car, concrete based parking and plain window glass are considered for heat transfer calculation at parked condition without air conditioner (AC) on. For heat gain calculation, the following steps are taken:

The local solar time, inclination angle, hour angle, altitude angle, and surface azimuth angle are calculated using the standard formulae for Kharagpur location for 21st June from 7 am to 4 pm local standard time [13]. The tilt angle for the front and rear wind shield are 48^o and 49^o respectively as per original car geometry. The angle of incidence for the roof, left and right walls, front and rear windshields are calculated for east facing car [13]. Similarly, the total incidence radiation (I) at Kharagpur and the direct solar radiation (I_{DN}), diffuse solar radiation (I_{Diff}), and reflective solar radiation (I_{Ref}) on front windshield, rear windshield, left and right wall with windows and roof are calculated by using standard equations for June month [11, 13]. The roof and side walls are made of combination of sheet metal, air gap and insulation material. Based on their thickness and conductivity, the overall heat transfer coefficients are calculated and shown in table 1 [11].

Table 1: *Calculated overall heat transfer coefficient (U-value) of roof and side walls of parked car in W/m^2.^{o}C.*

Roof	Side wall
0.541	0.533

Under parked condition the average velocity of wind, V is 2 m/s, based on actual measurements. The outside heat transfer coefficient [14] is given by

$$h = 0.6 + 6.64V^{0.5} \tag{1}$$

As the car is exposed to solar radiation during parking, inside cabin temperature changes with time due to heat gain. The surface temperature of the roof and side wall can be found by energy balance between the incident direct, diffuse and reflective solar radiation and combined heat transfer into the cabin. The generalized equation both for wall, glass and roof is given below.

Outside surface temperature and car internal temperature during parking can be found by equations 2 and 3.

$$\alpha(I_{DN} + I_{Diff} + I_{Ref}) = U_{wall/Roof}(T_{Surface} - T_i) + h_o(T_{Surface} - T_{\inf in}) \tag{2}$$

$$\sum[U_{Wall/Roof} A_{Surface}(T_{Surface} - T_i)]_{Wall/Roof} + \sum Q_{WS/WG} = DTM\frac{\delta T_i}{\delta t} \tag{3}$$

For calculating the cabin interior temperature, the deep thermal mass (DTM) is calculated by summing up multiplication of mass and heat capacity for all the interior elements including air. The calculated value of DTM is 793.5 KJ/K. Then the heat gain through the wall, window glass, windshield and roof are calculated by using equation 4.

$$Q_{Surface} = U_{Surface} A_{Surface} (T_{Surface} - T_i) \quad (4)$$

Where, $T_{Surface}$ and $A_{Surface}$ are the surface temperature and area, respectively. For window glass, outside air temperature is taken as glass outside temperature. When the solar ray enters the car directly through windshield and window glass then the heat load is calculated by equation 5.

$$Q_{SG} = A_{Glass} (\tau I_{Total} + N \alpha I_{Total}) \quad (5)$$

Similarly, heat gain through all surfaces are calculated for south, west and north facing car.

For calculation of cooling load of running car, the altitude angle is varied with respect to time. The car cabin temperature is maintained at 25 °C by keeping the AC on. For running car same Eq. 1 is used for calculating heat transfer coefficient where car velocity is varied from 20 km/h to 75 km/h [14]. The cabin total heat gain (assumed to be equal to cooling load) for the running car is the summation of instantaneous heat transfer due to solar radiation, metabolic heat of occupant, ambient load, and engine load. Solar radiation load through the roof, side walls and window glass are calculated by equations 2 to 5. When there is no direct solar radiation through the window glass the ambient load is calculated by equation 4.

The cooling load in the cabin due to engine heat [15] is given by

$$Q_{Engine} = S_{Engine} U (T_{Engine} - T_i) \quad (6)$$

Where, T_{Engine} is the engine surface temperature, which varies with engine RPM and is given by

$$T_{Engine} = -2e^{-6} RPM^2 + 0.0355 RPM + 77.5 \quad (7)$$

The value of the engine rotational speed is 3500 RPM and engine surface area is 1.239 m^2.

The metabolic load of passenger and driver are calculated as per their activity by:

$$Q_{Met} = \sum M A_{DU} \quad (8)$$

Metabolic heat production rate (M) for driver and passenger are taken as 100 W/m^2 and 75 W/m^2 as per ASHRAE [11]. An estimate of the body surface area as a function of height (H in m) and weight (W in kg), called the DuBois area A_{DU} (in m^2), is computed [16] by equation 9.

$$A_{DU} = 0.202 W^{0.425} H^{0.725} \quad (9)$$

The cooling load due to tailpipe emission is neglected as this is very small because of good floor insulation. The cooling load of the running car is varied with varying car speed and altitude angle. The total cooling load of the running car with and without direct radiation through the front windshield and occupants is the simple algebraic summation given by,

$$Q_{TotalSH} = \sum Q_{Surface} + \sum Q_{SG} + \sum Q_{Ambient} + \sum Q_{Engine} + \sum Q_{Met} \quad (10)$$

3. RESULTS AND DISCUSSION

3.1 Effect of orientation of parking on heat gain

The orientation of car parking under the sun affects the heat gain because of the large glass area of the windshield and windows. Fig. 4 shows that for the white car parked on concrete base, facing towards north gives rise to maximum heat load followed by south orientation at 10 hours on 21st June (without metabolic load). So, if the car is parked west facing up to 12 hours and after that east facing then the total heat gain of the day will be minimum compared to other orientations.

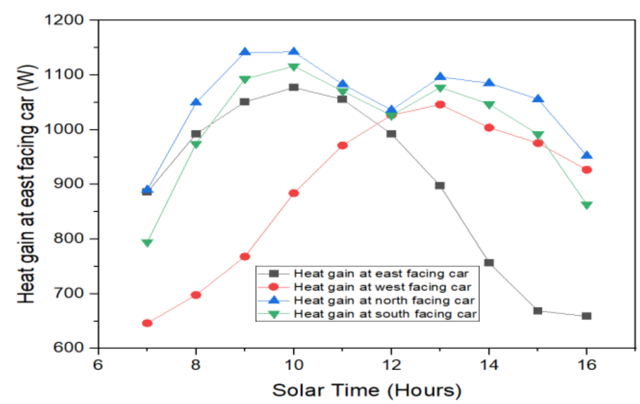

Fig. 4 Variation of heat gain of white car on concrete parking with normal window glass

3.2 Effect of car colour and parking base material on heat gain

As the absorptivity and reflectivity of different colours or coating materials are different, they affect heat gain on car. Fig. 5 shows that there is around 14% reduction of heat gain for north facing white car parked on grass base compared to black car parked on concrete base with same orientation. Similarly, among the white, light colour, medium dark and black colour cars parked south facing on grass base, white colour car gains least heat throughout the day as per Fig. 6. At 12 hours the sun is at overhead and no entry of direct rays into the car through glass that is why the heat gain reduces at 12 hours.

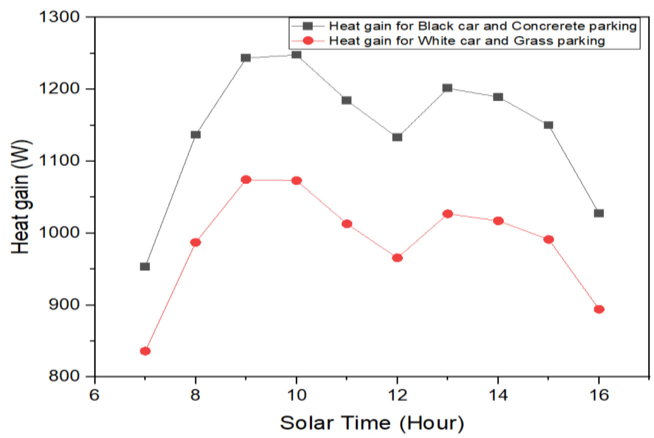

Fig. 5 Comparison of heat gain of black car with concrete parking and white car with grass parking for north facing

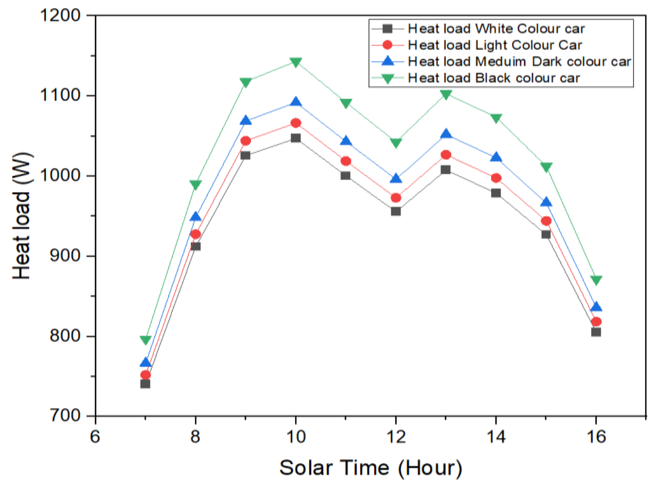

Fig. 6 Comparison of heat gain of south facing various colour car with grass parking and normal glass

3.3 *Effect of normal and tinted glass of window and rear windshield on heat gain*

Normal glass passes most of the solar radiation compared to tinted glass. Fig. 7 shows that % reduction of heat gain for white car with tinted glass is maximum for west facing at forenoon and for east facing at afternoon as the front windshield is not tinted glass.

There is a maximum 22.5 % reduction of heat gain when white car with tinted glass parked on grass base compared to black car with normal glass parked on concrete base. The cabin temperature is maximum and minimum for north facing and west facing car respectively as per Fig. 8.

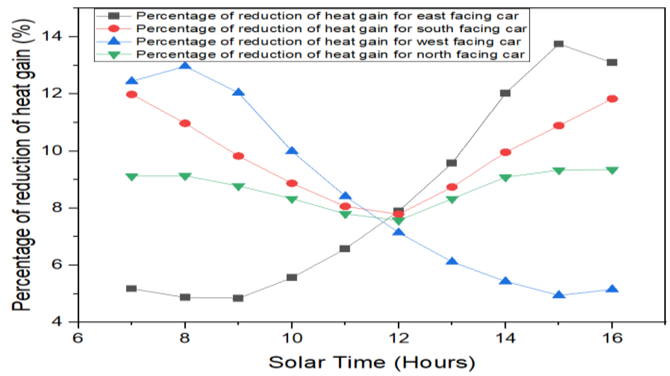

Fig. 7 Percentage reduction of heat gain for white car on concrete parking due to tinted glass for different facing car

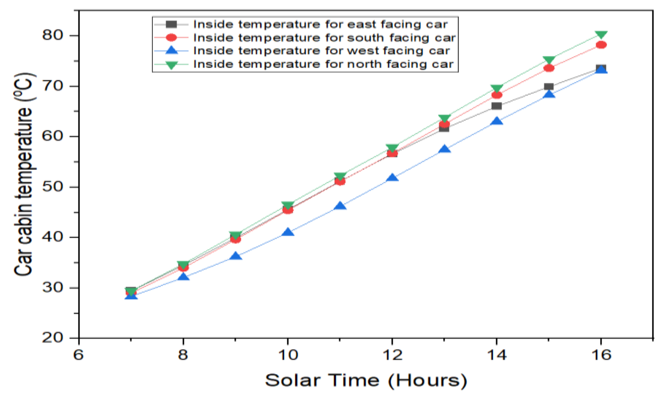

Fig. 8 Variation of car cabin temperature for white car parked on concrete base at different orientation

3.4 *Effect car speed on surface temperature, heat transfer coefficient and heat transfer*

At parked condition the heat gain of the car is extreme but as the car starts to run, the cooling load decreases with velocity as the surface temperature starts reducing. Figure 9 shows how the heat transfer coefficient increases and surface temperature and heat transfer of roof into the cabin reduce with increase of velocity.

The cooling load of the car strongly depends on the insulation materials. Among the various materials generally use for car insulation, aerogel has least thermal resistance, 0.0155 m-K/W. In this analysis rubber infused closed foam is used and its resistance is 0.1801 m-K/W and because of that there is 3 % cooling load reduction. The total cooling load of the car varies with respect to number of occupants because of variation of metabolic heat. The total cooling load at 12 hours for four occupants and direct solar radiation into the cabin through the front windshield is 1286 W.

There is 61 % increase of cooling load at 8 hours if the solar rays directly enter into the car cabin through front windshield while running.

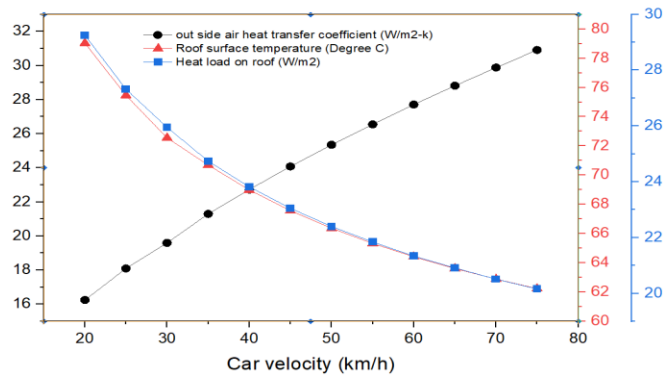

Fig. 9 Variation of roof temperature, heat transfer coefficient and heat flux through roof with car velocity

4. CONCLUSIONS

The results show that the orientation of the car during parking affects the heat gain substantially. Ideally to minimize this, the car should be parked west facing up to 12 hours and after that it needs to be parked east facing. As expected, the car colour and characteristics of the parking space play very important role. White car and grass base parking zone contribute least heat gain compared to concrete base materials. As the cooling load reduces with car velocity so the car should be driven at optimum speed which reduces the cooling load. Use of proper window glass and insulation leads to noticeable reduction in cooling load of the car.

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